Developing gamma-ray tracking with a segmented Ge detector

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Abstract. Basic techniques that make it possible to trace the gamma-ray interactions inside a segmented Ge detector and reconstruct the gamma-ray trajectory are discussed. The process of developing gamma-ray tracking in general and the plans for establishing the position sensitivity of the iThemba LABS segmented clover detector are outlined.

1. The idea about developing gamma-ray tracking

Some fifteen years ago the most powerful gamma-ray arrays, GAMMASPHERE and EUROBALL, were delivering plenty of gamma-spectroscopic data with the aid of which many new phenomena in nuclear structure were discovered. These powerful arrays consisting of gamma-ray detectors were covering a solid angle of 4π, with a total photopeak efficiency of about 9% for a gamma-ray with energy of 1.3MeV. Nevertheless the question whether we can improve even further the resolving power of the gamma-ray arrays was discussed.

The GAMMASPHERE and EUROBALL arrays consisted of a large number of HpGe detectors, each surrounded by a Compton-suppression shield made of scintillator detectors. The Ge crystals which are the active material for gamma-ray detection covered about 50% of the 4π solid angle. The Compton-suppression shield is used to veto the gamma-rays that Compton scatter outside the Ge crystal after depositing part of their energy, and thus they contribute to an unwanted Compton background. The BGO shield then improves substantially the Compton background and therefore the resolving power of the array. But one can consider whether the performance of the array may not be enhanced by replacing the scintillators with Ge crystals, making in that way a full 4π ball made entirely of Ge crystals. In this case when a gamma-ray scatters from one Ge crystal to a neighbouring one, instead of rejecting the event, we can measure all deposited energies and sum them to recover the total energy of the incident gamma-ray.

In order to implement this idea there is one problem that needed to be solved. Assume that two Ge crystals were hit, and the deposited gamma-ray energies were E_1 and E_2. One needs to determine whether these two hits were caused by one gamma-ray with a total energy of $E = E_1+E_2$, that scattered between the two crystals, or whether they were two independent gamma-rays with energies of E_1 and E_2 respectively. It is obvious that in the latter case the two energies should not be summed.

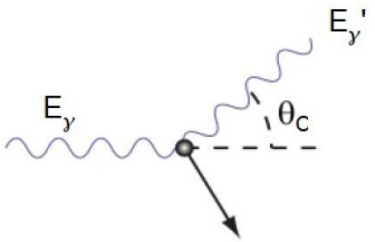

Figure 1. Diagram showing Compton scattering of a gamma-ray

In fact one can easily distinguish a Compton scattering event by testing whether the deposited energies E_1 and E_2, and the scattering angle θ_C (see figure 1) obey the Compton scattering formula:

$$\cos \theta_C = 1 + 0.511(1/E\gamma - 1/E\gamma')$$

where the deposited energies are $E_1 = E_\gamma - E_\gamma'$ and $E_2 = E_\gamma'$

In order to test that equation we need to measure not only the energies, but also the scattering angle θ_C. Therefore the detectors need to have an extra capability, that is to be able to measure the position at which the gamma-ray interaction occurred.

The latest developments in gamma-ray detector technology made it possible to construct such detectors. These detectors are made of segmented Ge crystals and are a new generation of gamma-spectroscopy detectors. They have one central electrode where a high voltage with positive polarity is applied, while the outside electrode is segmented. For example the segmented Ge crystal used in the AGATA and GRETA arrays (shown in the figure 2), is segmented in 6 x 6 = 36 segments. In comparison another segmented Ge detector, a TIGRESS detector, is also shown in figure 2 and has a 4 x 2 = 8 segmentation per Ge crystal.

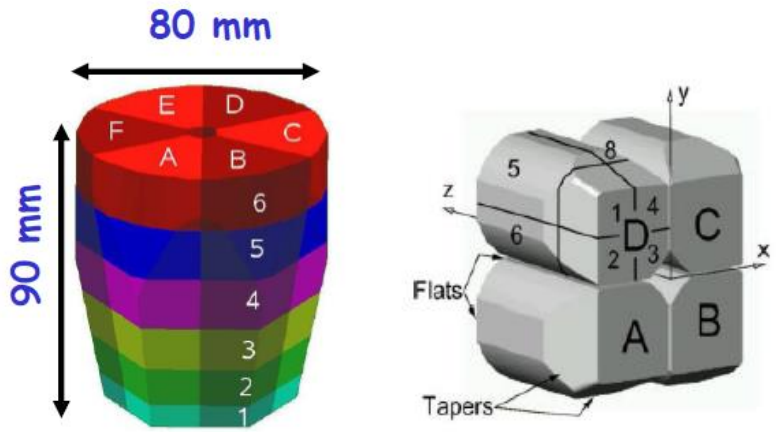

Figure 2. Left: the AGATA/GREATA Ge crystals, segmented in 6 x 6 fold. Right: TIGRESS detector with a segmentation of 4 x 2 = 8 fold per crystal.

When a gamma-ray interacts inside the detector, it creates charges. These charges move towards the electrodes creating electric currents. The signals observed on the electrodes represent such currents and have shapes that are indicative of the mobility of the electron and hole charge carriers, and also of where (i.e. how far from the electrode) the charge was created. A few examples for shapes of the signals created at different positions are illustrated below.

The signals shown in figure 3 are measured for a TIGRESS detector. Three interaction points are illustrated as black, red and blue dots. The corresponding signals on the three outside electrodes, C1, C2 and C4 are also shown in the figure. The interaction points plotted in red and black are situated at the same radius with respect to the core electrode, so they are at approximately the same distance from the electrode C1. That is why the black and the red signals on the electrode C1 have approximately the

same shapes. The signal for the blue interaction point however shows a distinctly different shape, because this point lies at a different radius.

The amplitudes of the induced signals on the neighbouring electrodes C2 and C4, can be used to determine how close each interaction point is to these electrodes. For instance the signals measured at electrode C2 indicate that the blue and the red interaction points are lying at approximately similar distance from the electrode C2, while the black interaction point is closer, because this signal has a larger amplitude. In a similar way we can deduce that the red interaction point is closer to electrode C4 then the black and the blue interaction points because the signal from the red interaction position has a larger amplitude.

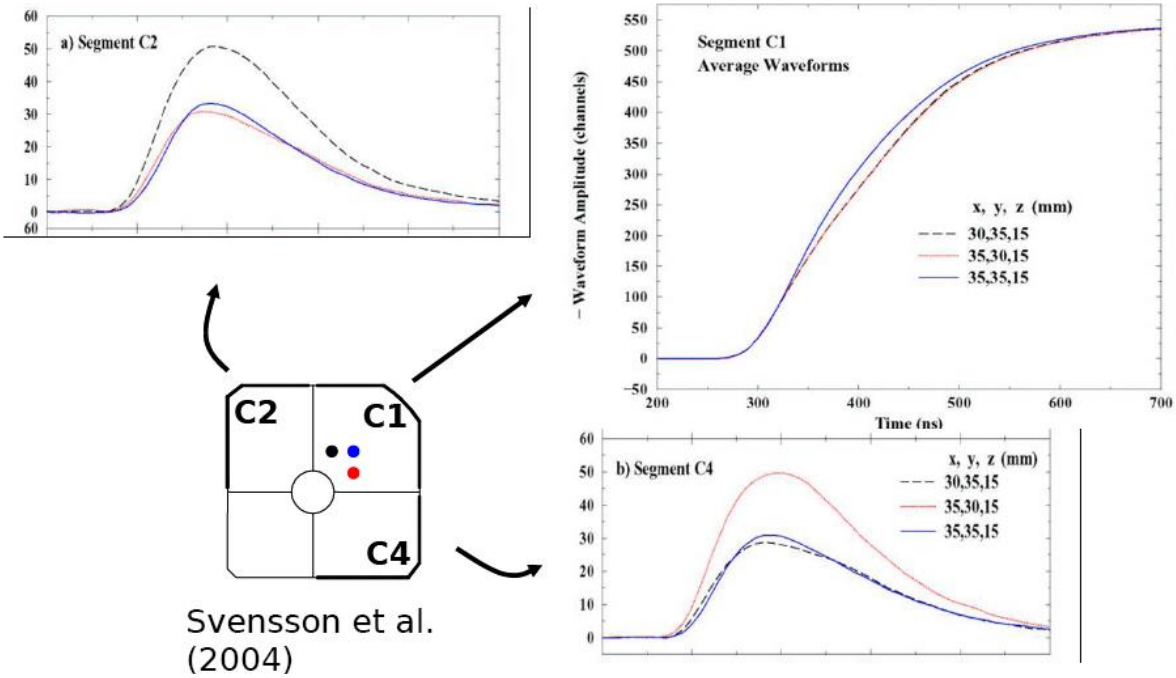

Figure 3. Signals measure for a TIGRESS detector for three different interaction positions shown with black, red and blue. From [1].

In fact the set of signals measured at all electrodes is unique for each interaction point. It is also different for different type of detectors and even for different detectors with the same geometry. That is because the shape of the signals depends not only on the geometry of the detector, but also on the high voltage value, on the impurity concentrations, and on the specific characteristics of the particular crystal preamplifier.

To utilize the position sensitivity of a segmented Ge detector we have to create a data base containing sets of pulses that characterize every possible interaction position in the volume of the detector. Then an experimentally measured set of pulses associated with certain gamma-ray interaction points, have to be compared with the data base. The best match will then determine the exact position of the gamma-ray interaction.

Once the interaction positions associated with a gamma ray are deduced, the gamma-ray trajectory needs to be recovered by determining the correct order of the set of gamma-ray interaction points. This is usually done by applying a tracking algorithm that checks which ordering of the interaction points satisfies the Compton scattering formula.

New gamma ray arrays, able to implement this gamma-ray tracking technique were designed, such as AGATA and GRETA. They have typical efficiency of about 43% for 1.3 MeV gamma rays, and resolving power of 2-3 orders of magnitude larger than the GAMMASPHERE and EUROBALL

arrays [2]. Smaller versions of these arrays, called AGATA demonstrator and GRETINA are already in operation.

2. Advantages of gamma-ray tracking

Gamma-ray tracking was suggested and developed as a necessary technique to build a 4π array of Ge detectors. However the gamma-ray tracking has other additional advantages. Successful gamma-ray tracking leads to:

(i) efficient add-back, i.e. recovering the total energy of a Compton scattered gamma ray,

(ii) efficient rejection of the Compton background, better than what can be achieved with a typical Compton suppression shield

(iii) precise measurement of the position for the first interaction point of the gamma ray inside the detector. This offers unprecedented accuracy and precision for several experimental techniques, such as: lifetime measurements using Doppler effects, correction of Doppler shifts for gamma rays emitted by nuclei in flight (that improves substantially the energy resolution and the resolving power of the detector), angular distribution measurements which can yield precisely measured mixing ratios and g-factors, etc.

(iv) precise measurement of the position for the second interaction point of the gamma ray inside the detector. This offers unprecedented precision for linear polarization measurements, and allows establishing the electric or magnetic nature of the gamma ray.

3. Developing gamma-ray tracking with the iThemba LABS segmented clover detector

The iThemba LABS segmented clover detector is a detector with TIGRESS geometry – it consists of 4 Ge crystals, each 8-fold segmented, as shown in figure 2. Each crystal has a diameter of 60mm before shaping and a length of 90 mm. It is designed to be placed at 14.5 cm or 11 cm from the target and is complemented by a Compton-suppression shield. Simulations yield efficiency of 0.63% and 1% for a 1.3 MeV gamma ray at these two distances [3].

The major interest in the iThemba LABS segmented clover detector lies with its position sensitivity. The wish is to use this detector for applications requiring extreme precision in the measured position of the first and second interaction points. To develop the gamma-ray tracking capacity of this detector the following major steps are planned:

(i) Simulations of the geometry, electric field, movements of the charge carriers and finally the shape of the pulses on the 36 contacts of the clover detector. Creating a data base with characteristic pulses for each interaction position.

(ii) Experimental verification of the simulations by measuring the pulses observed at several different well-defined interaction positions inside the iThemba LABS segmented clover detector.

(iii) Developing a procedure to compare the experimentally measured pulses with the pulses in the data base and extracting the best match to determine the position of the gamma-ray interaction.

(iv) Based on the established interaction positions the full gamma-ray track inside the detector will be reconstructed, yielding in particular the first and the second interaction points.

The development of gamma-ray tracking with the iThemba LABS segmented detector is under way. Results obtained so far from the simulations of the detector are discussed in the presentations given by S. Noncolela and T.D. Bucher. The experimental measurements of the performance of the segmented detector are discussed in the presentations of J.L. Eason and O. Shirinda. It is anticipated that once the gamma-ray tracking capacity of this detector is developed, it will be used as a new-generation gamma-ray detector for performing new types of nuclear structure experiments utilizing its position sensitivity.

4. Acknowledgement

The financial support from NRF for purchasing the segmented detector is gratefully acknowledged.

References

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